

THE ARC IN HIGH VACUA

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS
HOPKINS UNIVERSITY, IN CONFORMITY WITH THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

BY
R. E. LOVING

BALTIMORE

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INTRODUCTION

If a discharge tube is made with the electrodes placed opposite and extending very close to each other, e. g., 1 mm apart, one may observe the following phenomena as the pressure is gradually reduced. With pressure of the order of 1 mm of mercury, the current passes in the form of the ordinary purple glow. As the pressure is lowered, the luminosity of the gas decreases, and there is a noted increase in the potential difference necessary to cause the discharge to pass. This last fact is strikingly illustrated in the classical experiment of Hittorf.¹ Professor Thomson, in his theory of the discharge through gases, has shown that the potential difference necessary to produce the discharge in a vacuum tube must become very much greater if the distance between the electrodes is made less than the length of the negative dark space at the existing pressure. If the potential difference between the electrodes is still further increased by putting a spark-gap in series with the tube in the circuit leading to the electrical machine, cathode rays are given off strongly even at a pressure of 1 mm. When a pressure of a few thousandths of a millimeter is reached, if the external spark-gap is increased to 2 or 2.5 cm, the profuse cathode discharge and the attendant phosphorescence over

¹ *Wied. Ann.*, 21, 96, 1884.

the surrounding glass walls vanish, and the current passes in the form of a brilliant spark or arc between the electrodes.

Soon after the discovery of the Roentgen rays, Professor Rowland,¹ in the course of some experiments on the source of the radiation, noticed in one of his tubes, having aluminium electrodes about 1 mm apart, that when the pressure was extremely low, the discharge passed as a "spark or arc" between the electrodes. He observed that the spot of light on the anode was the seat of very strong Roentgen radiation. Professor R. W. Wood,² working independently, published about this time a paper on "A New Form of Cathode Discharge and the Production of X-Rays, together with Some Notes on Diffraction," in which he noted many of the properties of the discharge and mentioned some points deserving further study.

GENERAL STATEMENTS

Before taking up in order the several lines along which this investigation was directed, I shall give a brief description of the arc as I have produced it. Then I shall indicate the view which I was led to take concerning the nature of the discharge. Thus will be made apparent the points chosen for special study, the results of which have substantiated the view adopted. There will also appear the grounds on which I have chosen to speak of the discharge as an arc, although it is of course intermittent.

The electrode which I have found to give the most intense light are platinum beads about 1.5 mm in diameter, easily made by fusing the end of a platinum wire in the oxyhydrogen flame. If the vacuum is good, say a few thousandths of a millimeter, and the beads are placed 2 or 3 mm apart, the cathode rays go off in every direction from the negative electrode, but principally in the horizontal plane normal to the cathode wire and containing the negative bead. If now a spark-gap of 2 or 2.5 cm is introduced in the circuit leading to the machine, and the electrodes are brought nearer together, when they are within about 1 mm of each other, the phosphorescence on the walls of the vessel vanishes, and there appears the brilliant light on the anode bead.

But while under these circumstances there was no phosphores-

¹ *Physical Papers*, p. 574.

² *Physical Review*, 5, 1, 1897.

cence on the walls of the outer tube, there was a bright glow on the small capillary tube into which the anode wire was sealed (see Fig. 3), extending several centimeters beyond the seal. This phosphorescence on the anode tube did not appear at relatively high pressures, but only when the pressure and distance between the electrodes were such as to cause a very high potential difference—i. e., only when there was a strong electric field around the electrodes. It was also observed that when this glow first became distinct on the anode tube, there was often a faint glow on the cathode tube also, but this did not persist at very low pressures or when a wide external spark-gap was introduced. A tube having platinum-wire electrodes sealed into bulbs joined by a capillary showed that when the potential difference between the electrodes was not too high, cathode rays were given off with very rapid alternations by each wire, principally by the normal cathode, and less by the electrode joined to the positive pole of the machine. The discharge from the machine was therefore under these conditions oscillatory, as was shown also by a telephone placed in the circuit. Thus the occasional appearance on the cathode tube of the phosphorescent glow, such as persisted on the anode tube, but nowhere else when the potential difference between the electrodes became very high, was due to its being temporarily an anode. The persistent phosphorescence on the anode tube is due, I think, to two causes. Some cathode rays shot off from the cathode toward the anode do not strike the bead, but go just by its edge, and, moving parallel and very close to the anode wire and tube, are drawn in by the very strong field about the tube and so strike against it, causing the phosphorescence and a feeble emission of Roentgen rays. Moreover, there is a small quantity of gas present in the vessel, and gas is being given off continually by the beads, particularly by the anode, which suffers disintegration, so that the pressure about the electrodes is probably appreciably higher than the average pressure in the system which is registered by the gauge. Since this gas about the electrodes, and especially in the region around the positive wire and tube, is ionized by the cathode rays which go past the positive bead, we may expect that the electrons or negative particles thus set free will be drawn in toward the anode, and in moving through the high potential gradient near the anode tube will acquire sufficient energy to cause

phosphorescence. Such an accelerating action of the positive electrode on the cathode rays is illustrated in many Roentgen-ray tubes, where it is found that the emission by the anti-cathode is markedly increased if this is made the anode or is joined with the anode. In fact, instances may be cited in which the anti-cathode gave no evidence of even a feeble Roentgen radiation unless it was made anode, in which case it became a strong source. If the above explanation of the glow on the anode tube is correct, we should expect that any screen or obstacle, placed in close to any part of the anode wire or tube so as to obstruct a section of those cathode rays which pass by the anode beads, would produce at most only a shading in the glow on the tube, and not a complete shielding; for there would still remain the effect due to the electrons set free in the surrounding gas by the stray cathode particles.

After the arc has commenced to pass steadily, the distance between the electrodes may be increased to 1.5 mm, provided the vacuum is maintained by pumping (for the evolution of gas by the electrodes is considerable). Under these circumstances, which are the most favorable for observing the discharge, the source of light has not the form of a continuous line reaching from one bead to the other, as is the case with the ordinary spark, but rather looks like a crescent on the outer or near surface of the anode. The accompanying drawing will make my meaning plain. This brilliant light is usually surrounded by a sort of halo or corona, the color of which depends on the metal of the anode. This halo was most marked with a magnesium anode, and was of a yellowish-green color. If the discharge runs for some time, the end of the anode is markedly disintegrated. Red-hot particles are shot off from the end of the anode in every direction. This effect was most striking in the case of a titanium anode, when the luminous particles were shot off in great numbers, and often suffered several reflections from the walls of the vessels while still glowing. This disintegration of the anode is of course more marked for the volatile metals. There is also a deposit on the end of the cathode, and the amount of this deposit is apparently proportional to the loss of the anode. Two especially well-formed deposits and craters were noticed with a platinum cathode and magnesium and iron respectively as anode. I give in Fig. 2 a sectional view of the anode and cathode, before the discharge and after it had run

for about two hours. If the vacuum was about 0.001 mm and the external spark-gap was closed so that the discharge became less intermittent, the anode bead was intensely heated; the small platinum bead could thus be raised to a white heat in a minute or less. This heating of the anode is of course only an example of the well-known action of cathode rays on any obstacle against which they strike. If the discharge is intermittent, there is time between the showers for the heat to pass off by radiation and conduction along the wire. Again, if the pressure is not extremely low, the potential gradient is not great enough for the cathode particles to be given sufficient energy to cause visible heating by impact. If the anode, instead of being a bead on a small wire, was a small bar of metal 1.5 mm in diameter, no visible heating effect could be produced, conduction in this case being too rapid.

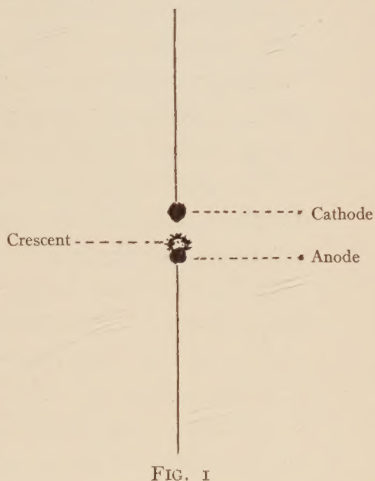


FIG. 1

Having observed that the anode wastes away as in the ordinary arc, that the light belongs to the anode rather than to the two elec-

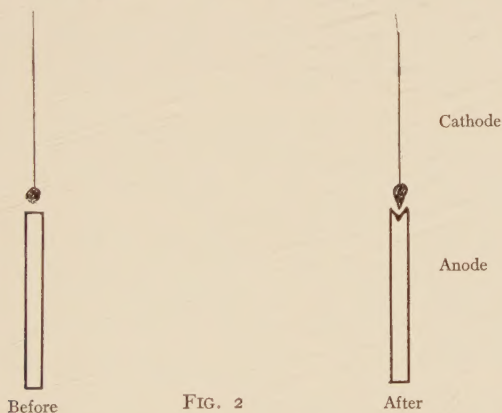


FIG. 2

trodes equally, that it is much more intense than the ordinary spark in air between the same electrodes with the same source of current, that the anode is (under certain conditions) visibly heated, I have

chosen to designate the discharge by the word "arc"; not meaning that I consider it similar to a uniform steady arc, but rather that it is in these respects analogous to the arc, and, when the anode is markedly heated, possesses the essential characteristic of the arc. The fact that the light is emitted by the bombarded anode, and that the luminosity as well as the heating of the anode seems to be due to the violent impact of the cathode particles, makes it plain that the discharge cannot be strictly an arc or a spark, for no such conditions exist in either as they are commonly produced. The phenomena might seem to approximate more nearly to a possible state of things in the chromosphere, where we may think of the matter as suffering severe impacts of the small parts against each other, due to the falling in, under the Sun's attraction, of material from the outer portions. Hence it was that I have studied the spectra of such substances as show strong chromospheric lines. Moreover, from the experiments of Hartmann¹ and others it appears that the conditions for the existence of the so-called characteristic spark lines are fully met in this case, so that we should expect in advance to find these, whether or not there are also present characteristic arc lines.

OBJECT OF INVESTIGATION

In the study of this discharge the points which seemed to merit special investigation were:

What becomes of the cathode rays when the profuse phosphorescence on the walls of the tube vanishes and the brilliant little arc appears?

What is the action of a magnetic field on the arc?

Is there any change in the current when the above-mentioned change in the discharge takes place?

What is the nature of the spectrum of the light emitted—does it correspond in general to the characteristic spark or arc spectrum, and is the character of the lines at all similar to the corresponding chromospheric lines?

APPARATUS

The vacuum was produced with a Geissler-Toepler mercury pump, and the pressures were read with a McLeod gauge. The source of current was always a six-plate Toepler-Holtz electrical machine.

¹ *Astrophysical Journal*, 17, 270, 1903.

This was used rather than a coil, since such a machine gives a practically constant potential and unidirectional current. If working under favorable weather conditions, the current from the machine was about 0.15 milliamperes on closed circuit and 0.1 milliamperes with an external spark-gap of 2.5 cm in series with the tube. These readings were made on a Roentgen ammeter, kindly furnished by the Roentgen Manufacturing Co. of Philadelphia. It was in every case necessary to have one of the electrodes movable, hence the discharge apparatus was always mounted on a glass tube about 85 cm long, dipping into a mercury basin. The lower electrode was sealed into a glass tube bent into the form of a U, one arm extending up the long glass tube in which the mercury formed a barometer column, the other being held in a clamp which was movable by a slow motion screw. The particular form of tube and other apparatus depended on the experiment in hand, and will be described in connection therewith.

EXPERIMENTS ON CATHODE RAYS

The vacuum apparatus used in all experiments in this connection was a small bell-jar, 8 cm in diameter and 20 cm high, fastened to a ground aluminium plate with stopcock grease (prepared according to the formula of Travers:¹ 1 part vaseline, $\frac{1}{8}$ part paraffin, 2 parts rubber. The lower electrode was always connected to earth. The platinum wires *P* and *Q*, on which were fused the electrode beads, were sealed into capillary tubes, as thin-walled tubing was often punctured by the discharge, which seemed to prefer a path of 10 or 15 cm to the very short one between the beads. The tube carrying the electrode *P* was sealed into the mouth of the jar *J* with Khotinsky wax, and the aluminium plate *A* was similarly fastened on to the barometer tube *H*. Through *H* there passes, alongside the electrode tube, a glass rod *R* bent into a U at the bottom, and at the top into a shape indicated in the figure, so that any kind of phosphorescent screen or obstacle could be mounted on this rod by being fastened on to a small piece of glass tubing which fitted rather snugly over the end of the rod. This cap could be made secure and rigid by a little wax warmed and put on the end of the rod as the cap was pushed down over it. The rod *R* is capable of a rather

¹ *Study of Gases*, p. 24.

wide vertical motion, so that any part of any mounted screen could be brought opposite either of the electrodes *P* and *Q*. A limited freedom of rotation of *R* about itself as axis made it possible to bring the screen up to the electrodes or to hold it quite out of the line of the discharge.

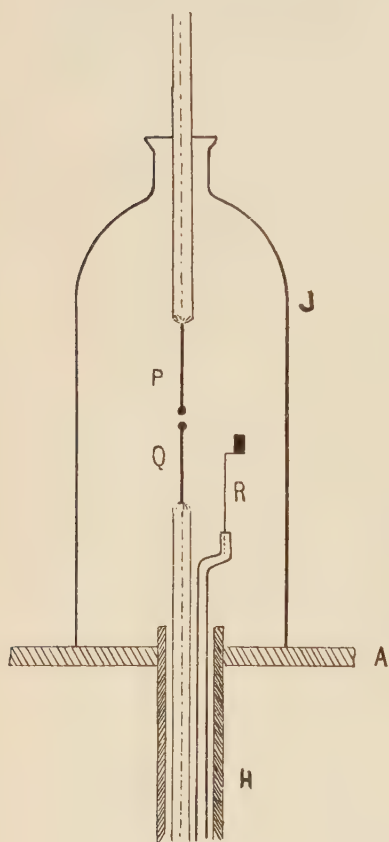


FIG. 3

Now, the very intense emission of Roentgen rays by the end of the anode very near to the cathode in a highly exhausted tube, as has been already alluded to, might seem to indicate a sort of focusing, so to speak, of the cathode rays on the anode surface just next to it. Moreover, some Roentgen-ray graphs taken by the writer with a pinhole camera seem to indicate that the surfaces most vigorously bombarded by the cathode rays during the arc discharge are the opposite surface of the anode, the wire, except just above the bead, and the more or less blunt end of the glass tube into which the anode wire is sealed. It may be remarked that on a plate obtained with a two-hour exposure at a distance of about 10 cm from the source there is no impression of the cathode, so that there seems to be no Roentgen radiation at the starting-point of the cathode particles. A distinct impression was made by the lower surface of the anode in three minutes.

Hence it was thought that, after the arc was formed, the distribution of the cathode rays was probably such as the following, viz.: the principal part of the discharge passes across directly from one electrode to the other, and the few cathode particles, shot out at a small angle with the vertical and going past the anode bead, are deflected by the electric field, which is very strong on account of the

extremely low pressure and the nearness of the electrodes. These are thus drawn in toward the anode, and so strike against the anode wire or the glass tube farther on. To test the views which I have indicated concerning the distribution of the cathode rays, and the cause of the persistent glow on the anode tube, the following experiments were made.

A small piece of copper foil about 5 mm square, and coated over with burnt ruby dust, which phosphoresces with a bright red color under the cathode rays, was mounted on the rod *R* (Fig. 3) with its plane vertical and perpendicular to a radius of the jar. By means of the rod the screen could be moved in a vertical or horizontal plane. Before the arc formed, if the screen was opposite the cathode bead or any part of that wire, there was a bright glow on the side of the screen next to the electrode and a weaker glow on the opposite side, the latter being evidently due to the diffuse cathode radiation from the walls of the jar. After the arc was formed there was no glow on the screen until it was moved up to or above the level of the upper bead, which was anode. In such a position, however, there was now a glow on the outside of the screen (though there was no radiation from the walls of the vessel) and none on the inside next to the electrodes. If the screen was moved up very close to the glass tube carrying the anode, there was a weakening of the phosphorescent glow on this tube, but not a complete shadow. A very strong phosphorescence was seen on the edge of the screen next to the cathode when the screen was so placed that its lower edge was opposite to or above the anode bead and was close in to the axis of the discharge. The fact that during the arc discharge there was, for the above-mentioned position of the screen, a glow only on the far side, shows that the cathode particles in the region are moving with appreciable velocity only toward the anode. This glow is thus due principally to the electrons generated in the region and drawn toward the anode by the electric field. The much stronger glow on the edge of the screen next to the cathode shows that, besides these secondary rays, there are some which come directly from the cathode against this edge.

Such a screen as was described above was then mounted with its plane horizontal. Before the arc passed, if the screen was on the

cathode side of the gap, there was a glow on the surface facing the gap. But if the arc was formed, there was no phosphorescence on the screen for such a position; but if it was moved opposite the anode wire or bead, and brought in very close to the wire, the glow appeared on the side facing the cathode; and this glow was much more intense on the parts of the screen nearest to the electrode wire. This was more marked if the screen was placed near the anode wire just beyond the bead. This screen, as the one above referred to, failed to cast any distinct or sharp shadow on the anode tube, which, as I have said, phosphoresced brightly for several centimeters beyond the seal of the platinum wire. This experiment also tends to confirm the opinion that some particles leave the cathode in a direction slightly inclined to the vertical and pass around the anode bead, but that most of them are confined to a region very close to the anode.

Besides the metallic ones, several mica screens were used, also screens or obstacles made of newly drawn small soda-glass wires. The phenomena were in each case similar to those of the experiments described above, and suggested the same explanation.

Now, with a fairly low pressure and small external spark-gap, it was often noticed that the phosphorescence on the bell-jar was confined to a narrow zone including the plane of the cathode bead, thus showing that the particles were shot out horizontally. As the necessary conditions for the arc were more nearly satisfied, the phosphorescent zone moved toward the anode end of the jar and became progressively less defined. The preceding experiments show that when the discharge passes as the arc, the cathode particles outside of the arc-gap are confined to the region close around the line of discharge and (excepting secondary radiation) are moving parallel to the discharge. It therefore seemed of interest to investigate whether there was a gradual change in the path of the rays from along a horizontal to a vertical direction.

A mica screen about 2 cm square, coated with ruby dust, was mounted with its plane vertical, and almost but not exactly containing the electrode wires. This gave sections of the cone of rays sent out by the cathode, and the shadow of a short glass wire which pierced the screen showed their path. Again, a mica disk mounted horizontally, and having a small hole in its center, could be placed

by means of the rod *R* in any desired position above or below the gap. As the cathode particles are at times shot out horizontally, and then, when the potential difference is increased, in a direction making an acute angle with the line joining the cathode to the anode, it was thought that the horizontal screen would indicate the angle at the vertex of the cone of rays from the cathode, and show whether this angle decreased continuously till the discharge passed as the arc; when, as already observed, no cathode particles make any large angle with the vertical. No result pointed to any other conclusion than that the change from the non-luminous to the so-called arc discharge was abrupt. There was no continuous and gradual concentrating of the rays along or nearly in the vertical, although the latter distribution always accompanied the arc. Furthermore, it was noticed that even when the mica disk was just opposite the end of the glass tube into which the anode was sealed, there still remained the phosphorescence for 3 or 4 cm along the anode tube.

I then determined to look more especially for the source of the persistent phosphorescence on the anode tube near to and just above the seal of the platinum wire into the glass. A small glass wire, about 1.5 mm in diameter, was bent into a ring large enough to go over the anode tube and leave a space of at least 1 mm all around. This was mounted on the rod *R* and, as the arc passed, was moved into various positions along the phosphorescent portion of the anode tube. Sometimes there seemed to be a faint shadow, but the cases were irregular and uncertain. Two little glass wires, about 3 mm long, stuck on to the anode tube radially, also failed to cast any distinct shadow along the tube. Bits of platinum wire gave similar results. The phosphorescence along the tube at points 2 or 3 cm from the end was then not caused principally by the glancing impact of rays shot out from the cathode and moving in paths only slightly inclined to the axis of the discharge.

Again, a thin glass disk, having in its center a hole just large enough for it to slip over the *Pt* beads, was mounted on the rod *R*. No position of this screen, whether just in the plane of the anode bead or quite up against the seal of this wire into the glass tube, gave any appreciable weakening of the glow on the anode tube. A small piece of glass tubing, 3 cm long and 2 or 3 mm larger in diameter

than the electrode tube, was mounted with the disk so that the two formed a sort of cap for the anode tube. This larger tube produced a very distinct shading, but there was still considerable phosphorescence on the protected or screened parts, although no primary cathode particles could strike the anode tube, and no secondary ones except such as were generated within the inclosing tube. The only explanation which occurs to me of the phenomena in question is that the glass surface of the disk and of the short outer piece of tubing, being struck by primary and also by secondary particles, emits into the inclosed space some radiations which, under the action of the strong field, bombard the anode tube and also act as ionizers. Since this space was very limited, the number of ions generated, and so the number striking against the anode tube, was smaller than if the tube had been removed, and so there was less intense phosphorescence than on portions of the anode tube that were not thus enclosed.

ACTION OF A MAGNETIC FIELD

In studying the action of a magnetic field on the discharge, the vacuum apparatus was a glass tube about 3 cm in diameter having a T-tube sealed into one side just opposite the electrodes and covered at its end with a glass plate sealed on with wax. In the first experiments to be described this side tube was normal to the plane of the axis of the magnet and the line of the discharge, and was 5 or 6 cm long, so that the glass plate would not blacken so rapidly with the platinum deposit; for the arc was observed through this side tube. The arrangement is shown in the drawing on the following page, except that the side tube is here a very short one along the axis of the magnet, which was a later arrangement. *N* and *S* are the conical pole-pieces of the electromagnet; these are bored through the center, so that when desired the arc can be viewed by looking along the axis *AB* of the magnet. A variable resistance in series with the exciting coils enabled the strength of the field to be altered at will. With low pressures, say 6 or 7 thousandths of a mm, if the external spark-gap was adjusted and the electrodes so placed that the arc was just on the point of forming—i. e., passed irregularly—the effect of the magnetic field was to cause the arc to pass regularly or steadily; the field seemed then to aid the formation of the arc discharge.

Again, the magnetic field often caused the anode bead to become visibly heated. Both of these actions may arise from the fact that a magnetic field in general hinders the discharge.¹ Here, then, its effect is to cause an increase in the potential difference between the electrodes, and is thus analogous to a lowering of the pressure.

As evidence of the fact that cathode rays have a very much higher velocity when the magnetic field is on, the following phenomenon may be mentioned. If the arc is not passing, but we have the phosphorescent glow over the tube, the magnetic field twists into spirals

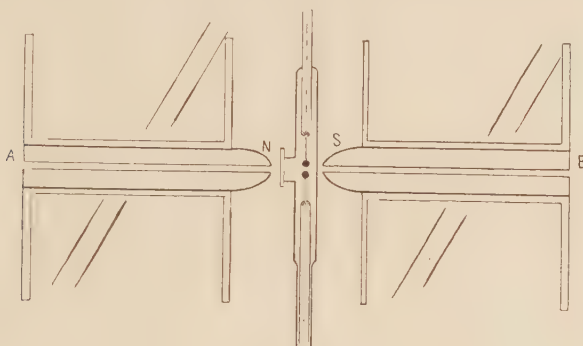


FIG. 4

(The oblique lines represent the Field Coils.)

the paths of all particles except such as are moving parallel to the field, and these therefore form on the tube a sort of image of the cathode. There thus remain two bright phosphorescent spots on either side of the tube, and the intensity of the glow is much increased in these images, as I call them. On cleaning the tube with aqua regia, it was found that in these places the glass appeared etched. It seems worth mentioning that this violent cathode discharge exerted some sort of deteriorating action on the walls of the tube around the discharge; for after a tube had been used for some days, it was found to crack very easily if put in the flame for any reason, and it was easy to break up the fragments of such a tube with one's fingers. I have never seen it stated that the glass of cathode tubes becomes specially fragile, and have no explanation to offer, but simply mention the fact.

As to a deviation along the normal to the plane of the electric and

¹ Thomson, *Conduction of Electricity through Gases*, p. 474.

magnetic force of the spot of light which marks the point of impact of the cathode particles, it need only be said that with such magnetic field-strengths as I could obtain, calculation showed that the possible deflection of the rays was less than could be observed, especially since the arc was not stationary, but wandered about over the anode slightly according as one part or another of the cathode was specially active.

It remains to be said that the magnetic field did not noticeably alter the distribution of the phosphorescent glow on the anode tube, though there was a slight weakening of the effect.

CURRENT MEASUREMENTS

Before I had the opportunity of using the Roentgen ammeter, I had made some readings with a small gas voltameter in order to see whether there was any appreciable variation of the current as the nature of the discharge changed. However, the current from the machine is very small and varies greatly with the weather conditions, so that I was not able to get any results which justified supposing that there was any material change in the current.

Measurements with the Roentgen ammeter did not show any change of current whether the discharge passed as the arc or whether there was the brilliant cathode glow over the tube, nor did the magnetic field have any readable effect. It is to be noted, however, that even a relatively large change in the resistance of the tube would make only a negligible change in the resistance of the whole circuit, including the machine itself, and that we do not have at hand a large source of current. Hence no large current changes should be expected for any of the variations which we have made in the conditions or nature of the discharge.

STUDY OF SPECTRUM

The spectrum of the discharge was produced with a Rowland concave grating of 60 cm radius. It was desirable to study specially the violet end of the spectrum, as most of the substances examined have the strongest lines in this region. Hence I used always a tube having a quartz window. The arrangement of the tube, slit, etc., is shown in the diagram. No lens was used, as the arrangement would have required a specially ground one of quartz, and very little would have been gained by it anyway. The time of exposure necessary

was about one or one and a quarter hours. The films used were Eastman Kodoid, orthochromatic. The form of the electrodes was for one a platinum bead, and for the other a small bar of the substance about 1.55 mm diameter, fastened in the end of a brass wire. This wire, about 3 cm long and having a screw socket joint in the middle was fastened rigidly to a heavy platinum wire sealed into the upper end of the U-tube. To change the electrode it was necessary only to lift off the bulb above the ground joint, unscrew the little brass end,

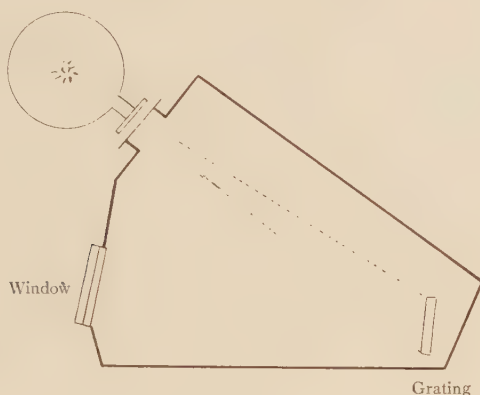


FIG. 5

and replace it by a similar one containing a different substance. For the calcium spectrum I used ordinary lime packed into a bored-out brass wire.

The first substances tried were *Mg* and *Pt* as anode and cathode respectively. There seemed to be no trace of *Pt* lines on the plate. It may be recalled here that I have said before that the light seemed to belong to the anode rather than to both electrodes; so I thought it worth while to test this point spectroscopically with two such metals as *Mg* and *Pt*, the one very easily volatilized and the other quite the opposite. I therefore carefully cleaned the *Pt* bead with acid and reduced the pressure to a few thousandths of a millimeter. If now the discharge was started with the *Pt* as anode, an exposure of as much as two hours failed to show any sign of the *Mg* lines. Of course, it was not possible to get the spectrum of the other electrode merely by reversing the current between exposures, on account of the previous deposit from the anode on the cathode. Nor was it possible to

reduce the pressure gradually and determine by eye observations at what pressure the anode only was active, for sufficient *Mg* got on the *Pt* anode to show in the spectrum even after the pressure was so low that the *Mg* cathode itself had ceased to play any part. In going from very low to higher pressures, the steps could not be made gradually, and so all that I can say is that so long as the pressure was low enough to cause the discharge to have the form of the little crescent of light on the anode, only the lines characteristic of the anode could be seen.

Having shown that the spectrum was characteristic of the anode only, if the discharge passed in the form which I have designated as the arc, I obtained the spectra of *Mg*, *Cu*, *Cr*, *Mn*, *Ti*, and *Fe*, respectively, by making anodes of these substances, the same *Pt* cathode serving throughout the series. Only the stronger lines made an impression on the plates in the time given an exposure; these, however, were amply sufficient for purposes of comparison such as I had in mind. The general character of the spectrum does not correspond to that of the arc or spark. (I could not take the ordinary arc or spark spectra on the same film with the spectrum of this anode light, and the intensities for these as given in the tables below are from Exner and Haschek.) Nearly all of the strong spark lines appear, and the spectrum is very much more like the spark than the arc. But the relative intensity is by no means the same for all the lines. Nor does there seem to be any close analogy between the intensities in this case and those of the chromosphere. There is observed here, however, an effect analogous to that brought out by Petaval and Hutton;¹ viz., certain lines have in this vacuum arc an intensity which is not at all in the same proportion to that of neighboring lines as in the ordinary arc or spark. It is doubtful if in this case the sole cause is diminution of pressure, but probably it is due both to the low pressure and to the fact that the luminosity is here excited under conditions materially different from those existing in the arc or spark in air.

I give below a list of the stronger lines showing on my plates, with their relative intensities in the ordinary arc and spark, chromosphere, and the arc as I have produced it in the vacuum tube. I shall designate these respectively by A, S, C, and Av.

¹ *Phil. Mag.*, 6, 569, 1903.

MAGNESIUM

λ	INTENSITY				λ	INTENSITY			
	A	S	C	Av		A	S	C	Av
2777.....	20	6		2	2929.....	.2	200		6
2778.....	20	5		1	2937.....	3	200		8
2780.....	30	10		3	3829.....	30	200	5	5
2782.....	20	5		1	3832.....	50	300	7	9
2783.....	20	6		1	3838.....	100	500	10	15
2791.....	5	100		12	4481.....	0	50	1	20
2796.....	200	500		10	5073.....				?
2798.....	2	100		8	5168.....			2	0
2803.....	100	500		8	5173.....			4	1
2852.....	500	100		8	5184.....			5	2

CALCIUM

3159.....	10	50		1	4289.....	50	20	5	0
3179.....	15	50		2	4299.....	30	20	1	00
3706.....	10	50	10	3	4303.....	100	50	2	3
3737.....	20	50	15	5	4308.....	30	20	5	0+
3934.....	500	1000	75	25	4318.....	50	30	1	1+
3969.....	300	500	60	20	4355.....	3	1		3
4227.....	1000	100	8	5	4435.....	100	20		1
4283.....	50	20	1	0	4455.....	200	30		2

CHROMIUM

2672.....	3	8		1	2980.....	2	10		2
2677.....	4	20		1	2985.....	2	10		1
2688.....	2	10		2	2989.....	1	10		1
2704.....	1	6		1	3016.....	2	3		1
2727.....	1	5		0	3027.....		8		1
2749.....	3	8		1	3041.....	4	10		2
2751.....	3	10		1	3050.....	1	10		2
2752.....	3	10		1	3119.....	3	10		1
2763.....	3	10		1	3120.....	3	15		2
2767.....	4	15		3	3125.....	3	20		3
2792.....		10		1	3132.....	4	20		4
2801.....	1	10		1	3147.....	2	5		0
2812.....	1	10		1	3368.....	3	20		1+
2818.....	1	8		0	3403.....	3	15		1-
2822.....	1	10		2	3409.....	1	20		1
2831.....	1	20		1	3579.....	30	20		2
2836.....	4	30		3	3594.....	30	20		2
2843.....	4	15		2	3605.....	30	20		2
2850.....	4	10		2	3964.....	6	8		1
2851.....	1	7		1	3970.....	5	8		1
2856.....	3	10		1	3977.....	6	8		1
2863.....	3	10		1	3984.....	4	5		1
2876.....	2	5		3	3993.....	3	3		0
2899.....	1	5		2	4254.....	50	50		4
2922.....	1	3		1	4275.....	50	30		3
2927.....		5		2	4290.....	30	30	1	3
2935.....	1	4		1	4337.....	10	8		1
2947.....	1	3		0	4345.....	10	10		1
2954.....	1	4		0	4352.....	15	10	1	2
2972.....	2	10		2					

MANGANESE

λ	INTENSITY				λ	INTENSITY			
	A	S	C	Av		A	S	C	Av
2576.....	4	30		5	2892.....	I	4		0
2594.....	4	15		4	2898.....	I	3		0
2606.....	4	10		4	2900.....	I	3		0
2610.....	I	8		I	2933.....	3	15		3
2618.....	2	8		2	2939.....	3	20		4
2626.....	2	7		2	2949.....	3	30		5
2633.....	I	7		2	3442.....	2	30		3
2638.....	I	5		2	3460.....	2	20		2
2640.....	I	5		I	3474.....	I	15		2
2656.....	I	4		0	3483.....	2	12		I
2667.....		4		I	3489.....	2	10		0
2702.....	I	5		2	3807.....	I	8		I
2706.....	I	8		2	3824.....	4	6		I
2709.....		4		I	4030.....	100	20		I
2712.....	I	5		2	4033.....	100	20		4
2719.....		3		I	4034.....	50	10		3
2795.....	50	4		2	4041.....	20	10		4
2805.....	I	5		I	4048.....	8	7		I
2813.....	I	3		0	4055.....	4	8		I
2815.....	I	3		I	4064.....	5	6		I
2831.....	2	3		0	4070.....	4	3		I+
2870.....	I	4		I	4235.....	10	20		I+
2880.....	I	5		I	4451.....	5	10		I+
2890.....	I	10		2					

TITANIUM

3168.....	5	15		0	3706.....	2	8		I
3191.....	4	10		0	3742.....	3	10		3
3202.....	3	10		0	3759.....	10	20		6
3234.....	8	15		2	3761.....	10	10		5
3236.....	5	6		2	3900.....	5	50		3
3239.....	4	6		2	3914.....	5	20		3
3242.....	4	10		I	4164.....	2	20		2
3249.....	4	10		I	4172.....	I	15		2
3262.....	4	15		I	4274.....	15	4		I
3323.....	5	10		2	4290.....	10	10		2
3329.....	6	10		I	4294.....	10	10		I
3332.....	3	8		I	4300.....	15	8		I
3335.....	5	10		I	4306.....	20	8		I
3342.....	4	10		2	4308.....	4	8		I
3349.....	8	10		4	4313.....	2	8	I	I
3362.....	I	30		3	4315.....	5	5		I
3373.....	4	20		3	4338.....	2	10		2
3384.....	3	20		3	4358.....				3
3505.....	3	30		3	4395.....	10	20		3
3511.....	3	30		3	4418.....	2	6	I	I
3520.....	2	8		I	4444.....	4	15	2	2
3536.....	2	15		I	4468.....	4	15	5	2
3625.....	2	8		I	4488.....	I	6		I
3641.....	15	10		I	4501.....	4	15	6	2
3660.....	3	10		I	4550.....	4	20	8	4
3662.....	2	10		I	4564.....	3	10	5	2
3685.....	8	100		5	4572.....	3	20	4	3

IRON

λ	INTENSITY				λ	INTENSITY			
	A	S	C	Av		A	S	C	Av
3735.....	50	10		I	4045.....	50	15	2	4
3749.....	30	10		3	4063.....	30	10		2
3758.....	30	8		I	4071.....	20	8		2
3763.....	20	6		I	4144.....	15	5		0
3816.....	20	10		0	4202.....	10	6		0
3820.....	50	10		I	4250.....	15	6		0
3826.....	30	8		I	4260.....	20	10	I	0
3841.....	15	5		I	4271.....	30	10		3
3860.....	30	6		I	4305.....	30	15		3
3878.....	15	5		0	4325.....	30	15		4
3886.....	20	5		I	4355.....		20		2
3928.....	15	4		0	4383.....	100	20	I	6
3969.....	15	5	I	0	4404.....	50	15	I	3
4005.....	15	6		0	4415.....	20	10	I	I

A comparison of these lists with those of Exner and Haschek will show that some strong spark lines are wanting on every plate, and many of the strong arc lines. With regard to the *Mg* group at λ 5183, it should be said that the small intensity given there is due to their being far in the green, where the plates were less sensitive. To the eye they appeared as strong as the line at λ 4481. It may be noted also that the *Mg* lines are much longer on the plate than those of any other substance. This is to be expected, as I have said before that the arc was surrounded by a much brighter halo with this metal than with any of the others. The strong *Hg* line at λ 4358 showed as a long line on every plate, the extensions above and below the arc being almost as bright as the central portion.

SUMMARY

The results of the foregoing experiments may be briefly summed up as follows:

If, at very low pressures, the discharge is caused to pass across a narrow gap, the cathode particles are shot off only by the near surface of the negative electrode, and almost all of them strike against the opposite face of the anode.

The principle action of a magnetic field on the discharge is to increase the potential difference in the gap, and consequently the kinetic energy of the cathode rays.

The luminosity of the anode is due to the violent impact of these cathode particles, and the spectrum of the light emitted is not analogous to that of either the spark or the arc. The fact that the spectrum is characteristic of the anode, and that the cathode makes no impression seems to merit special attention.

In conclusion, I wish to state that this research was carried on under the direction of Professor Ames. My best thanks are due to him for much valuable advice and criticism, and for the facilities placed at my disposal, and also to Professor Wood for many suggestions. The kindness and interest of student friends have been in many ways helpful.

BIOGRAPHICAL SKETCH

Robert Edward Loving was born near Wilmington, Va., April 20, 1874. His early training was received from an older brother, his sisters' governess, and the neighborhood high school. In October 1891 he left home and farm life to enter Glade Spring Military Academy, and in June 1892 he received the first prize, a scholarship to Richmond College. He was graduated M. A. from this institution in 1898, having been for his last two sessions assistant in Mathematics and Latin. In the autumn of the same year he entered Johns Hopkins University as a Graduate Student in the Department of Physics, Mathematics, and Astronomy. After remaining there three years he was awarded a fellowship in Physics. He was for the next two sessions principal of Churchland Academy, Virginia, returning to Johns Hopkins in September 1903. During his stay in this university he followed courses under Professors Rowland, Ames, Wood, Bliss, and Whitehead in Physics, Professors Cohen and Hulburt in Mathematics, and Professor Poor in Astronomy. He held appointments in the University as Virginia Scholar, 1898-1901 and 1903-4, Fellow in Physics, 1901-2 (did not enter on Fellowship), and Lecture Assistant to Professor Ames, 1904-5.

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